

## Determination of the band gap of semiconductors from the electrical measurement on respective diodes

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**Abstract** : Here, we report the determination of band gap from the forward voltage ( $V_f$ ) – temperature ( $T$ ) measurement at different current and capacitance ( $C$ ) – voltage ( $V$ ) measurements on semiconducting diode. From the analysis, it is concluded that latter measurement provides the correct information of the band gap unambiguously.

**Keywords** : Semiconductor diode, electrical properties, barrier height, band gap

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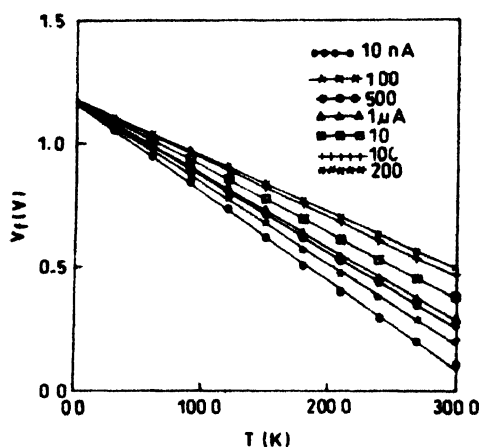
There are variety of techniques that have been used for the determination of the band gap ( $E_g$ ) for a semiconductor. One of them is the transmittance measurements which also envisages the nature of the optical transition (direct or indirect) [1]. But, the sample has to be in thin film form. It is also possible to determine the band gap of silicon and germanium by measuring the resistivity of the pure semiconductor as a function of temperature [2]. There are also reports on the determination of the band gap from the  $I$ – $V$  characteristics of respective diodes measured at different temperatures [3,4] and from the forward voltage ( $V_f$ ) – temperature ( $T$ ) measurements by extrapolating the curve to 0 K [5–7]. Here, we use different current values to determine the band gap from the  $V_f$ – $T$  measurements on their respective diodes. The determination of  $E_g$  from capacitance ( $C$ )–voltage ( $V$ ) measurements has also been reported [6]. The method is based upon the temperature dependence of Fermi level of the semiconductor the details for which has been discussed in Ref. [6].

The measurements were carried out from 10 to 300 K using an automated setup built around a Leybold closed-cycle refrigerator. The experimental details are given elsewhere [8]. The epoxy encapsulation of the diodes was ground flat on one side and fixed to the sample site with GE7031 varnish. Cigarette paper fixed with GE7031 varnish

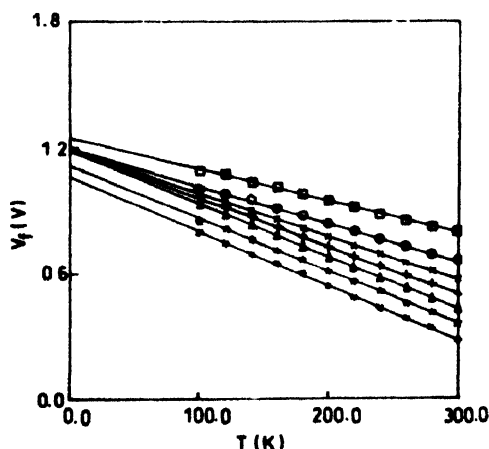
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provided the required electrical isolation. The electrical leads (insulated copper wires) are thermally anchored to the cold parts in order to reduce the stray thermal emf. The usual four probe electrical connections are made to the sample. A stable constant current was provided to the diode from Keithley model 224/2243 programmable current source. The forward voltage was measured using a Keithley model 182 digital voltmeter. The diodes are operated at a constant current ranging from 10 nA to 200  $\mu$ A while the voltage variation with temperature is monitored. This amount of current corresponds to a value below the knee in the  $V_f$ - $I$  characteristic of the diode in the entire temperature range studied. The temperature of the sample site is controlled using a calibrated type *D* silicon diode thermometer in conjunction with a Leybold model LTC60 temperature controller. The temperature is determined using the same silicon diode thermometer. This has a standard measurement accuracy of  $\pm 1\%$  or better.

The  $C$ - $V$  measurements were carried out at different frequencies in the temperature range 77 to 351 K using a home-built setup. The details of the experimental setup is published elsewhere [6]. For low temperature  $C$ - $V$  measurement the whole system is dipped in liquid nitrogen ( $\text{LN}_2$ ) in order to cool down the sample. For temperatures higher than the room temperature (298 K), the hole system is dipped in boiling water and maintained the distance between water level and the sample. The thermal contact between the sample and the thermocouple junction is made using GE7031 varnish. The temperature is monitored by using a chromel-constantan thermocouple whose one junction is at ice temperature and other is placed near the sample. The thermocouple output is measured using a Hewlett Packard 34401A multimeter. The voltage was provided to the sample from the HP4284A precision LCR meter and the capacitance was measured using the same meter. The oscillator level is set to 10 mV for all measurements.



**Figure 1.** The  $V_f$  -  $T$  characteristic of an 1N4007 Si diode for 10 nA, 100 nA, 500 nA, 1  $\mu$ A, 10  $\mu$ A, 100  $\mu$ A and 200  $\mu$ A of current in the temperature range 30–300 K. All the curves are least-square fitted and extrapolated to 0 K (shown by solid lines).



**Figure 2.** The  $V_f$  -  $T$  characteristic of a cryogenic silicon diode for 10 nA (lowest curve), 100 nA, 1  $\mu$ A, 10  $\mu$ A, 100  $\mu$ A, 1 mA and 10 mA (topmost curve) of current in the temperature range 100–300 K. All the curves are least-square fitted and extrapolated to 0 K (shown by solid lines).

Shown in Figure 1 is the  $V_f - T$  plot of an 1N4007 Si diode in the temperature range 30 to 300 K. The lower limit to the linear  $V_f - T$  region is usually that temperature at which carrier 'freeze out' occurs. In this region, the resistance of the diode becomes very large and the voltage increases rapidly with small decrease in temperature. Extrapolating to 0 K it is seen from Figure 1 that all the curves merge almost at a point irrespective of the current value. As discussed in Ref. [6] and [7], this gives the value of  $E_g$  which is found to be  $\sim 1.17$  eV in good agreement with earlier reported results [9].

We have also extrapolated the data of a different Si diode (cryogenic silicon diode supplied by the American Cryo Inc. [10]) as shown in Figure 2. On extrapolation to 0 K, it is noted from the figure that the curves do not merge at a particular point and hence, ambiguity arises in the determination of  $E_g$ . In this context, it is worth pointing out that the curves do not meet at a point because of the series resistance effect [7]. For current values  $1 \mu\text{A}$ ,  $10 \mu\text{A}$  and  $100 \mu\text{A}$ , the effect of series resistance is negligible and hence, the curves converge at a point in the voltage axis to give 1.19 eV as the value of  $E_g$ .

Figure 3 shows the room temperature measurement (300 K)  $C^{-2} - V$  curves of 1N4007 Si diode at different frequencies : 1 kHz, 100 kHz and 1 MHz. Frequency-dependent capacitance is observed where all the slopes converge to a common point. This implies that  $V_b$  is independent of frequency.

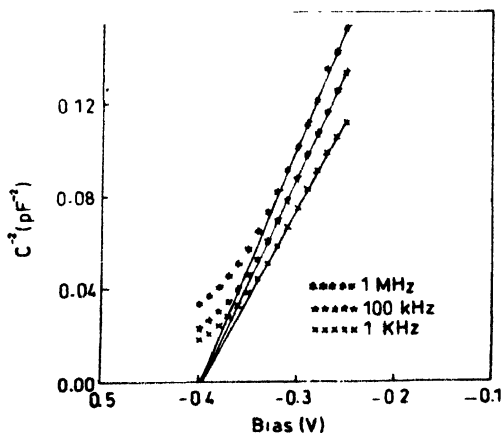
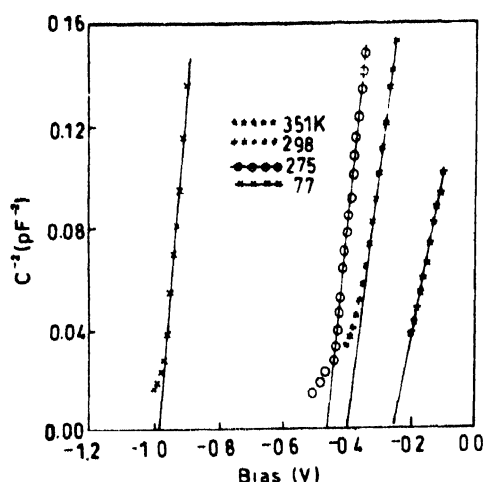


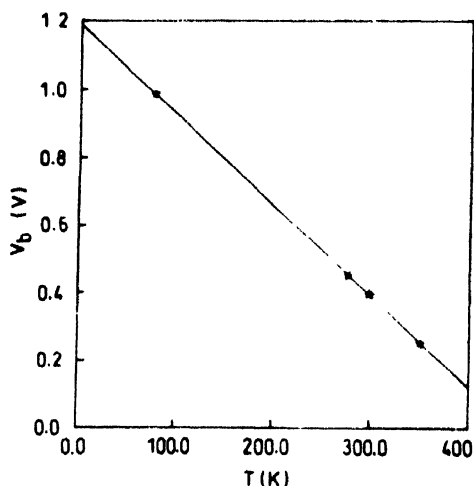
Figure 3. Capacitance voltage (298 K) characteristics of an 1N4007 Si diode at different frequencies

The  $C^{-2} - V$  curves of an 1N4007 diode at different temperature are shown in Figure 4. The frequency in all cases is 1 kHz. The barrier height  $V_b$  is obtained by extrapolating  $C^{-2}$  to zero. The temperature dependence of  $V_b$  are shown in Figure 5. As discussed in Ref. [6], the band gap at 0 K can also be determined from the  $V_b - T$  plot by extrapolating it to 0 K. Extrapolating to 0 K, the band gap is found to be 1.189 eV which is very close to the earlier reported results. Similar investigations carried out on different 1N4007 diodes and cryogenic diodes confirm the result quantitatively.

As the extrapolation of  $V_f$ - $T$  curve to 0 K yields different value for different current in the case of cryogenic diodes, ambiguity arises for the identification of  $E_g$ . But, there is no such ambiguity in the determination of  $E_g$  from  $C$ - $V$  measurements.



**Figure 4.** Capacitance-voltage (1 kHz) characteristics of an 1N4007 Si diode at different temperatures



**Figure 5.** The temperature dependence of  $V_b$  obtained from Figure 4 for an 1N4007 Si diode. Extrapolating to 0 K,  $E_g$  is found to be 1.189 eV.

In summary, the determination of the band gap  $E_g$  at 0 K from the electrical measurement of several semiconducting diodes is reported.  $E_g$  of silicon, estimated from the  $V_f$ - $T$  measurements on 1N4007 silicon diode is found to be  $\sim 1.17$  eV. But, ambiguity arises in the case of cryogenic diodes as the curves for different current do not merge at a particular point at 0 K. On the other hand, the band gap determined from  $C$ - $V$  measurement is very close to the earlier reported value and hence, can be used unambiguously for the determination of  $E_g$ .

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